# Wavelength Conversion at 10 Gb/s by Four-Wave Mixing Over a 30-nm Interval

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***Abstract*— We show that the use of a long semiconductor optical amplifier increases the error-free conversion interval of a four-wave mixing (FWM)-based wavelength converter. 30-nm wavelength down-conversion and 15-nm up-conversion have been obtained at 10 Gb/s. This result is a significant improvement over the previous best performance of a FWM-based wavelength converter and suggests that the full erbium-doped fiber amplifer bandwidth can be covered with FWM wavelength converters.**

***Index Terms*—Communication systems, frequency conversion, optical mixing, semiconductor optical amplifier.**

## I. Introduction

WAVELENGTH-DIVISION multiplexing (WDM) has been proposed to fully exploit the huge fiber transmission bandwidth [1] and to allow easy routing and switching in optical networks. In this frame, wavelength conversion has been suggested as a method of enhancing routing options and network properties like reconfigurability, nonblocking capability and wavelength reuse [2]. To achieve all-optical wavelength conversion, various strategies have been investigated [3], like cross-phase modulation (XPM), cross-gain modulation (XGM), and four-wave mixing (FWM) in semiconductor optical amplifiers (SOA's), of which only FWM, is transparent to both modulation format and signal bit-rate [4], while permitting arbitrary wavelength mapping. In particular, this technique can be used to convert digital as well as analog signals.

The use of FWM in optical networks is possible only if high conversion efficiency and high signal-to-noise ratio (SNR) can be achieved, the latter being one of the main constraints of the technique due to the high SOA amplified spontaneous emission (ASE). Two options are available to increase SNR: the use of high input power and/or the use of long amplifiers [5]. Recently, it was shown both theoretically and experimentally [6] that the use of long amplifiers dramatically enhances both the conversion efficiency and the SNR of converters based on FWM in SOA's. An increase of the efficiency of approximately 30 dB and of the SNR of 23 dB was obtained by increasing the length of the device from 0.5 to 2 mm [6].

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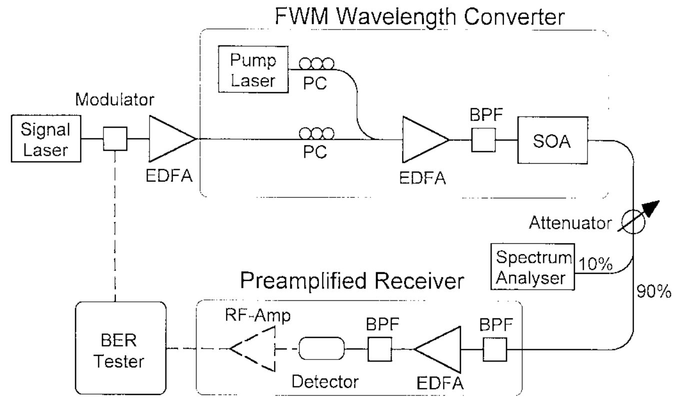


Fig. 1. Experimental setup. PC stands for polarization controller, BPF for banpass filter (all 1-nm bandwidth, except the one just before the SOA).

Wavelength conversion based on FWM in SOA's and working at a bit rate as high as 10 Gb/s, with low bit-error-rate (BER) degradation, has been demonstrated [7], [8] elsewhere. Here we show that the use of 1.5-mm-long amplifiers increases the available conversion interval, almost doubling the largest conversion interval previously reported at 10 Gb/s [8], [9] at BER values better than $10^{-9}$.

## II. Experiment

Fig. 1 shows the experimental setup used to evaluate the converter performance at 10 Gb/s modulation rate. This setup is similar to the one described in [8]. A fixed wavelength DFB semiconductor laser operating at 1558 nm and a tunable semiconductor laser are used alternatively as the pump and the signal. For wavelength down-conversion the input signal is fixed at 1558 nm, while the wavelength of the pump is tuned, whereas in the up-conversion case, the pump is fixed and the signal is tuned. The use of a high-power erbium-doped fiber amplifier (EDFA) in front of the SOA permits a total power injection in the SOA of about +15 dBm. The 15-nm bandwidth filter in front of the SOA is used to reduce the amplified spontaneous emission (ASE) from the EDFA outside the wavelength region containing the pump and signal and, in particular, at the conversion wavelength [9]. The power ratio between the pump and the signal is kept constant at about 10 dB, measured at the output of the SOA. This value

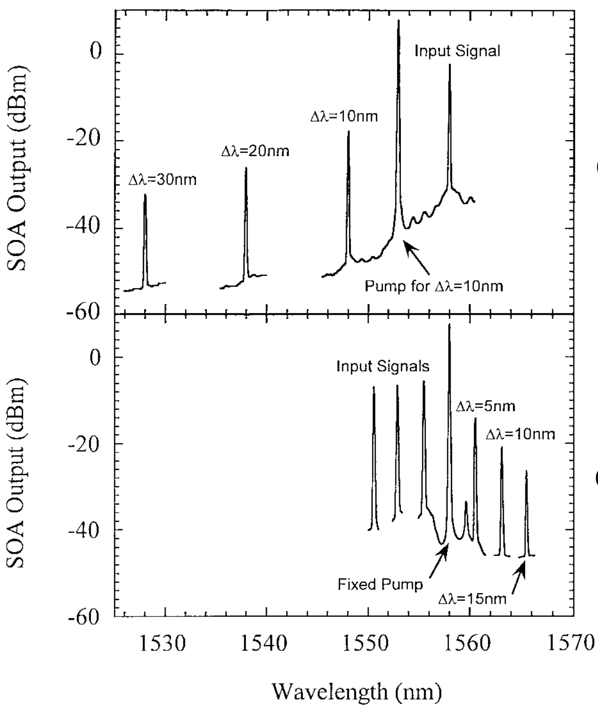


Fig. 2. Spectra of the pump, signal, and converted signal at the SOA output for different wavelength shifts. (a) Down-conversion. The signal wavelength is fixed at 1558 nm and the pump wavelength is shifted. (b) Up-conversion. The pump is at 1558 nm and the signal is shifted.

minimizes errors due to XGM of the pump by the signal, while maintaining a good conversion performance [10].

The SOA is a pigtailed bulk device with a ridge structure and coated angled facets [11]. Its length is 1.5 mm and the fiber-to-fiber small signal gain (approximately polarization independent) is limited to 24 dB at 1565 nm by the ASE-induced gain saturation. The detuning between the SOA gain peak and pump wavelength, in the up-conversion configuration, is about 7 nm without light injection, but increases to 17 nm under saturation. In these conditions, the spectral dependence of the gain and ASE is also strongly modified: for wavelengths shorter than the peak, gain and ASE suppression is much stronger than for longer wavelengths. The deformation and shift of the gain curve are detrimental in the up-conversion case. In this case, besides a lower FWM efficiency [12], [13], the converted signal lies in the region of maximum ASE, with a consequent decrease of the SNR. Better results are expected using amplifiers with the gain peak closer to the pump wavelength for high-injection conditions.

Fig. 2 shows the output spectrum for three different pump-signal detunings in down- and up-conversion configurations. The resolution bandwidth of the optical spectrum analyzer was set to 0.1 nm. The maximum detuning in down-conversion is limited to 30 nm by the bandwidth of the filter placed in front of the SOA, while in up-conversion it is limited to 15 nm by the converted signal-to-ASE-noise ratio. The output power reported in Fig. 2 is about 7.5 dB lower than the input power. This has to be ascribed to the high value of the output coupling loss under high saturation of SOA, which is caused by self focusing effects [14]. This was experimentally verified by using a similar SOA without fixed pigtails in which the

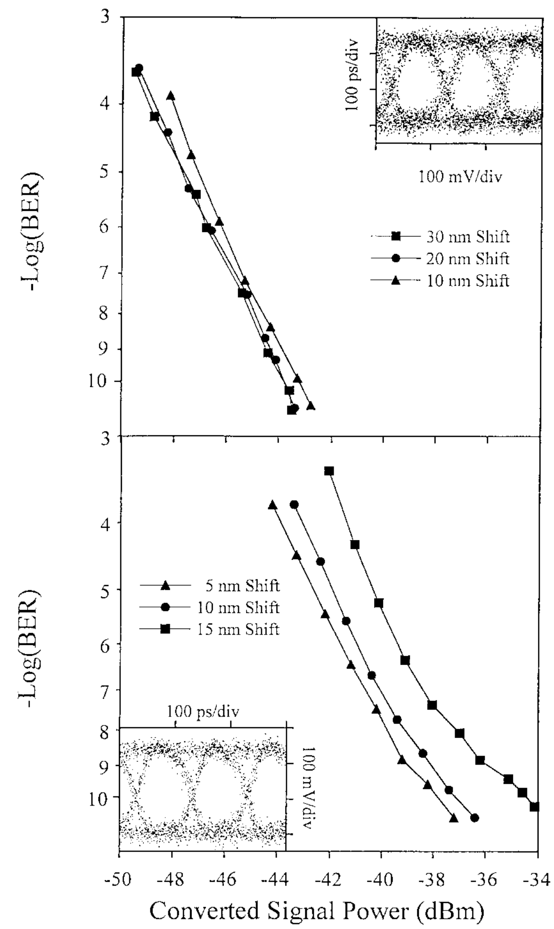


Fig. 3. BER versus power for selected (a) down-shift and (b) up-shift. In the inset, the eye diagram for the largest value of wavelength shift is reported.

distance for optimum coupling between the output lensed fiber and the SOA facet was reduced for high optical injection. The small peak at 1559.5 nm in Fig. 2(b) is due to a sidemode of the pump.

In Fig. 3, the BER curves versus power are given for the same values of pump-signal detuning of Fig. 2. In the inset, the eye diagram referring to the largest shift is reported. The spectral dependence of the receiver sensitivity does not allow an easy comparison of the BER curves. However, it can be observed that in down-conversion the BER curves are parallel with no evidence of any floor. The total shift of 30 nm covers the whole useful bandwidth of the EDFA and is limited only by the bandwidth of the prefilter and not by the conversion process itself. On the other hand, a degradation of the BER curves is observed in the up-conversion. This degradation is more evident for the maximum shift and is due to the ASE-induced low SNR. The appearance of a floor in the BER curves makes it impossible to achieve $10^{-9}$ error rate for higher wavelength shifts on the up conversion side. The degradation of the performance on this side is intrinsic to FWM [7], [13]: the conversion efficiency is lower and the ASE contribution is higher for up conversion. The use of longer amplifiers and a more accurate fit between the pump wavelength and the gain peak could improve the performance of the converter, and optimized gain-peak wavelength would increase the pump intensity in the device and reduce the ASE contribution at the wavelength of the converted signal.

## III. Conclusion

We have shown that the use of a long SOA improves the performance of a FWM based wavelength converter. We have almost doubled the maximum conversion interval so far obtained at 10 Gb/s in similar experiments. We have shown that, in the case of wavelength down shift, the whole band of the EDFA can be easily covered. The maximum obtained wavelength shift in the up-conversion is 15 nm and is limited by the lower conversion efficiency and the higher ASE noise in these conditions. The use of SOA's with the gain curve optimized to the pump could still improve the converter performance and further improvements are expected with longer SOA's.

*Note Added in Proof:* A paper on a 40-Gb/s wavelength converter over 24.6 nm, using FWM in a multiple quantum-well amplifier [15], was published after the submission of this letter.

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